DESIGN STUDY ON THE 1.3GHz SCALED SUPERCONDUCTING CAVITY FOR HIGH INTENSITY PROTON LINAC

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Abstract

In this paper an optimal design of the superconducting cavity for high intensity proton linac is illustrated and discussed in details the influences of the various geometric parameters of different cavity shape over SC cavity characteristics. On this basis, a scaled test cavity and its calculation results are presented.

1 INTRODUCTION

It is common knowledge that in late decade superconducting cavity has been widely used in electron accelerator because of its high accelerating gradient[1], and in some high intensity proton accelerator projects started recently including Waste Transmutation, Spallation Neutron Source and Tritium Production, superconducting accelerating structure is also the first choice. If a proton linac used in the medium energy high intensity accelerator, it might provide about energy 1~1.5GeV and its average current should be 10~200mA.

A study shows that a well established elliptical cavity ($\beta=v/c=1$) used in an electron accelerator is also adapted for much slower proton beams (β=0.4~0.9)[2]. While in a superconducting proton linac design, the whole linac need be divided into several sections, and each section should use same multi-cell cavities with the same β value. As a result, the accelerating cavity with fixed β value in the same section has different accelerating characteristics on the proton beam with different speed.

As a part of fundamental research of SC RF technology, we began our research on single cell niobium cavity with 700MHz, β=0.45. In order to save research costs, we study scaled cavity (1.3GHz) first, the same as most laboratories did when beginning its research on SC cavity. In this paper we present an optimal 1.3GHz scaled cavity shape by the way of analysis of different various geometric parameters influences over the SC cavity characteristics[3].

2 DESIGN CRITERIA

The main advantage of any SC cavity is the possibility of providing high accelerating gradient (E_{acc}). However there are two characteristics, which limit in principle an achievable maximum accelerating electric field. They are the peak surface electric field (E_{sp}) and the peak surface magnetic field (H_{sp}) of the SC cavity. E_{sp} is important because of the possibility of field emission in high electric field region leading to the sharp decline of the SC cavity characteristics. While H_{sp} is important because a superconductor will produce overheat and even quench above the critical magnetic field[4]. Theoretically speaking, its overheat critical field for high purity niobium cavity is about 2200-2400Oe and corresponding the highest surface electric field for a typical cavity shape is about 100MV/m. It is so far from what mentioned above, E_{sp} obtained up till now is only 50-60MV/m. That would mean that in order to obtain a maximized accelerating field, it is necessary to consider first of all the minimization of the ratios of peak fields to the accelerating field in the superconducting cavity design.

Besides, there are some more figures of merit to compare different designs such as unloaded quality factor Q_o, shunt impedance R_{sh}, etc. But it is different from the normal conducting cavity design that SC cavity unloaded quality factor is usually 5-6 orders higher than the normal conducting cavity. The above mentioned parameters, therefore, are not so crucial to the SC cavity design and may be varied in some limits without any obvious harm for the system as a whole.

Since the cavity cell length L_c depends on the cavity's β value, namely $L_c=\beta c/(2f)$, the SC cavity shape of the proton linac appears to be more flatter than the electron cavity. So the mechanical stability of proton SC cavity particularly deserves our attention. Generally speaking, the Lorentz force detuning coefficient K_L is not so sensitive to the cavity shape in high β case. But it is comparably more sensible for medium β cavity. The NASTRAN version 65 code can be used to calculate the cavity's stress. And the cavity structural analyses are carried out by using the ANSYS/ABAQUS codes. After known the cell deformation, the cavity detuning can be got by SUPERFISH code. In the engineering design, it is indispensable to utilize reinforced stiffener to increase the mechanical stability of a cavity.

The optimal cavity shape of a single cell cavity is a foundation for the multi-cell cavity design. As to the multi-cell cavity design, further consideration need be taken on a sufficient cell-to-cell coupling, a field flatness, and the higher order mode trap, etc..

3 CAVITY SHAPE VARIABLES

The cavity shape, 1/4 of cell, which we utilized to make the calculation, is shown in Fig. 1. Various geometric parameters of the cavity shape in the Fig. 1 are respectively as follows: the cell length L_c, the cavity diameter D, the iris radius R_i, the beam pipe length L_b, the equator length section L_{eg}, the slope angle α, the equator ellipse semi-axis A and B, the iris ellipse semi-axis a and b. The relation between every various geometric parameters would be determined by the equation

$$R_i + b - \frac{1}{2}D + B = \sqrt{k^2A^2 + B^2} + \sqrt{k^2a^2 + b^2} + \frac{1}{2}k(L_c - L_{eg}) \quad (1)$$

where the k=-$ctg\,\alpha$ and cavity geometry symmetrical center O is the coordinate origin.

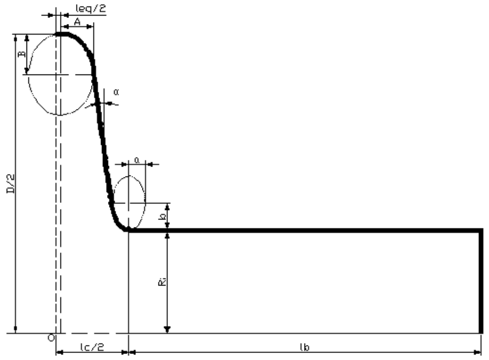

Fig. 1: Geometric parameter of an elliptical cavity (1/4 of cell).

Actually, an elliptical cavity design is a compromise between various geometric parameters which should define a most optimal cavity shape in terms of different accelerator purpose. For this reason, during our research on the effect of any geometry variable over the cavity characteristics, it is imperative to select a geometry variable to meet the requirement of design frequency. Meanwhile a free variable is also needed to satisfy the equation (1). The cavity diameter D is usually used as frequency tuning, this is because D is very sensitive to frequency (~7.34MHz/mm for our cavity) where as it affects little the electromagnetic characteristics and mechanical properties. As distinct from some designs in research on the influences of every geometry variable[2, 4, 5] over E_{sp}/E_{acc}, we take in most cases the equator ellipse A and B as free variatbls and optimization B/A to satisfy equation (1). This is because A and B have little effect on E_{sp}/E_{acc}. But if the iris ellipse a, b were selected as free variables[2], since the size of b has great effect on E_{sp}/E_{acc}, the influence of b would usually be brought upon the research results, thus causing the "sudden change direction" with the changing curve of research variables.

4 INFLUENCES OF CAVITY SHAPE VARIABLES OVER CAVITY CHARACTERISTICS

As we have mentioned above, we first of all take into account in the following research the influences of cavity shape variables on E_{sp}/E_{acc} and B_{sp}/E_{acc}, then on cavity's other characteristics as well.

4.1 Cell length L_c

Cell length L_c is determined by β value $L_c=\beta c/(2f)$. There is big difference of E_{sp}/E_{acc} between cavities with different β value (see Fig. 2). Higher β cavity has lower E_{sp}/E_{acc}, accelerating electron SC cavity E_{sp}/E_{acc} value usually closes to 2, while in a cavity with β=0.45, the E_{sp}/E_{acc} value is nearly 5. That is why we paid even more attention on the influences of variables on E_{sp}/E_{acc} in our optimal design of cavity shape.

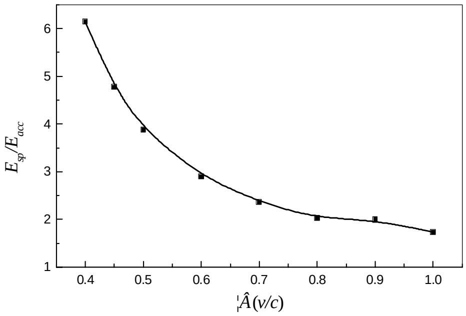

Fig. 2: E_{sp}/E_{acc} vs β value @ 1.3GHz

4.2 Iris radius R_i

With regard to iris radius R_i, there is great impact on many characteristics of SC cavity. You may see in Fig. 3, 4, 5 and 6, both E_{sp}/E_{acc} and H_{sp}/E_{acc} increase notably with

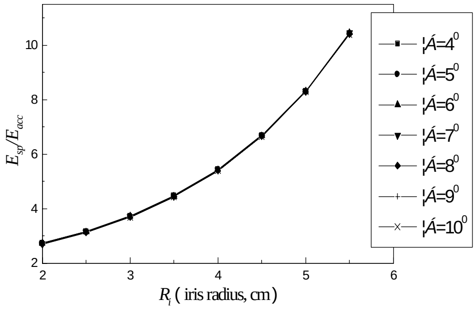

Fig. 3: E_{sp}/E_{acc} vs iris radius R_i

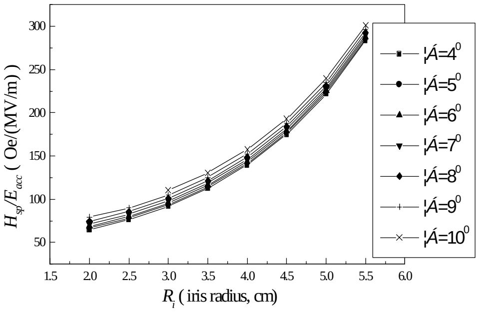

Fig. 4: H_{sp}/E_{acc} vs iris radius R_i

the enlargement of iris radius R_i. However, both cavity transit-time factor T and effective shunt impedance ZT^2 decrease with its enlargement. But cavity unloaded quality factor increase to a certain extent (see Fig. 7) with R_i enlargement. The cavity co-variables to be used in Fig. 3 ~ 6 are a=1cm, b=2cm, A/B=0.8, L_b=13cm, L_{eg}=0.4cm. Cavity iris radius R_i is considered in conjunction with beam dynamic calculations. Selection a larger R_i may decrease beam loss and avoid the higher order mode trap. As for a multi-cell cavity, R_i is often determined by the inter-cell coupling. The choice of a comparatively higher cavity inter-cell coupling factor k_c may be able to achieve comparatively even uniform field profile.

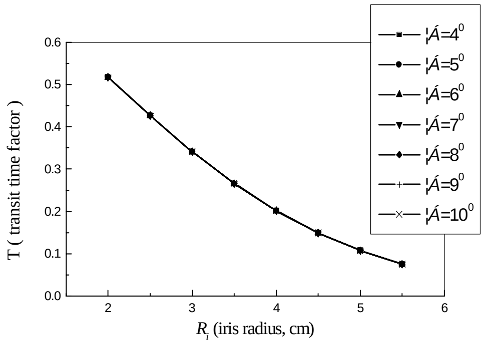

Fig. 5: Transit time factor T vs R_i

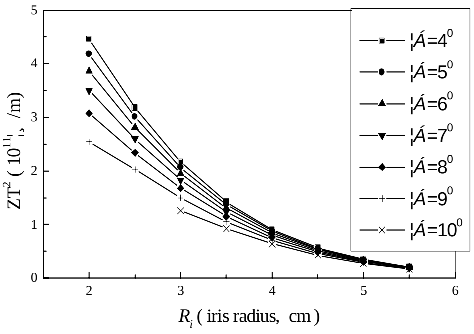

Fig. 6: ZT^2 vs iris radius R_i

To sum up, R_i is an important parameter which determines many characteristics of SC cavity. Given regard to such requirements as sufficient aperture ratio, inter-cell coupling and mode trap, minimized R_i should be selected to decrease both of E_{sp}/E_{acc} and H_{sp}/E_{acc}.

4.3 Slope angle α

You may see in Fig. 3, 4, 6, 7 and 8, α has little influences on both E_{sp}/E_{acc} and H_{sp}/E_{acc}. Even a larger iris radius R_i has as well little influence on ZT^2. But it does have some effect on cavity quality factor Q value.

Viewing from structural analysis angle, α should be even larger than 10^o if possible[6]. But for the middle β cavity, it is difficult to do so due to the limit of cell length. Although the cell rigidity may be raised by way of increasing wall thickness, it is still undesirable because of the poor thermal conductivity in pure Niobium material.

As for small angle cavity shape, it is a must to use reinforced stiffener in proper part of the cavity to raise cavity's mechanical rigidity.

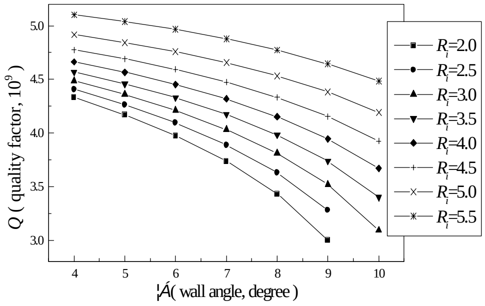

Fig. 7: Quality factor Q_0 vs wall angle α

4.4 Iris ellipse (a,b)

The shape of cavity iris ellipse has obvious influence on cavity surface electric field. If a larger b (vertical ellipse semi-axis) is chosen, E_{sp}/E_{acc} would be smaller, and consequently b/a would have a best value, while E_{sp}/E_{acc} might be minimized if b is under invariable condition (see Fig.8, in which α=5^o, R_i=3.8cm, $A/B=0.8$). In our research of cavity, selection of b=3cm, b/a=3 obtains lower E_{sp}/E_{acc}.

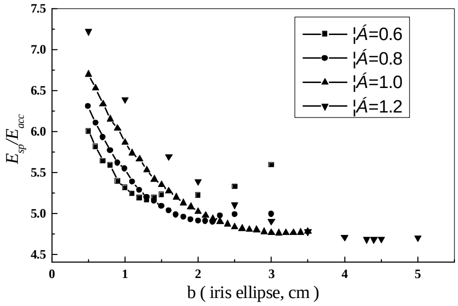

Fig. 8: H_{sp}/E_{acc} vs iris ellipse b

4.5 Equator ellipse (A,B)

Equator ellipse variates A, B or B/A has little influences on cavity electromagnetic characteristics (see Fig. 9), therefore A, B might be used as the free variates in cavity shape study, yet it has obvious influence on mechanical characteristics. The calculation shows[9], the round equator provides a K_L value of -6.8Hz/(MV/m)², and going to an ellipse with a ratio B/A=2, the K_L reaches the value of –9.0Hz/(MV/m)², i.e. an increase of about 30%. Considering from this angle, B/A trending to 1 should be selected.

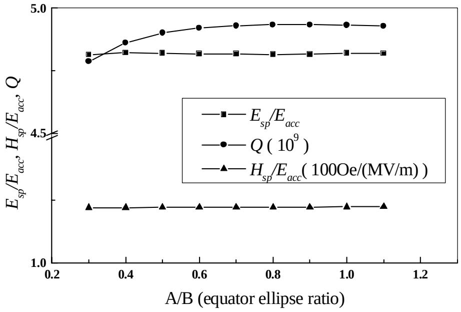

Fig. 9: E_{sp}/E_{acc} , H_{sp}/E_{acc} and Q_0 vs A/B

5 OPTIMIZATION OF CAVITY SHAPE

Based on the above analyses, the geometrical parameters of our 1.3 GHz, β=0.45 single cell scaled SC cavity are as follows:

Cell length: L_c=49.86mm
Cavity diameter: D =215.82mm
Iris radius: R_i=38mm
Beam pipe length: L_b=130mm
Equator length section: L_{eq}=4mm
Slope angle: α= 5°
Equator ellipse: A =10.83mm, B=21.66mm
Iris ellipse: a =10mm, b=30mm

The electromagnetic characteristics was calculated by SUPERFISH as follows:

Resonate frequency: f =1296.07MHz
Unload quality factor: Q_0 =4.41×10^9 @2K
Geometry factor: G=117.8Ω
Ratio of effective shunt impedance to unloaded quality factor : r/Q_0 =7.284Ω
Ratio of surface peak electron field to accelerating electric field: E_{sp}/E_{acc} =4.616
Ratio of surface peak magnitic field to accelerating electric field: H_{sp}/E_{acc}=125 Oe/(MV/m)

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